

The theoretical predictions for the study of the $a_0(980)$ and $f_0(980)$ mesons in the ϕ radiative decays. *

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February 1, 2008

Abstract

The potentialities of the production of the a_0 and f_0 mesons in the ϕ radiative decays are considered.

The central problem of light hadron spectroscopy has been the problem of the scalar $f_0(980)$ and $a_0(980)$ mesons. It is well known fact that these states possess peculiar properties from the naive quark ($q\bar{q}$) model point of view, see, for example [1, 2, 3, 4]. To clarify the nature of these mesons a number of models has been suggested. It was shown that all their challenging properties could be understood [1, 2, 3, 4] in the framework of the four-quark ($q^2\bar{q}^2$) MIT-bag model [5] with symbolic quark structure $f_0(980) = s\bar{s}(u\bar{u} + d\bar{d})/\sqrt{2}$ and $a_0(980) = s\bar{s}(u\bar{u} - d\bar{d})/\sqrt{2}$. Along with the $q^2\bar{q}^2$ nature of $a_0(980)$ and $f_0(980)$ mesons the possibility of their being the $K\bar{K}$ molecule is discussed [6]. During the last few years it was established [7, 8, 9] that the radiative decays of the ϕ meson $\phi \rightarrow \gamma f_0 \rightarrow \gamma\pi\pi$ and $\phi \rightarrow \gamma a_0 \rightarrow \gamma\eta\pi$ could be a good guideline in distinguishing the f_0 and a_0 meson models. The branching ratios are considerably different in the cases of naive quark, four-quark or molecular models. As has been shown [7, 8, 9], in the four quark model the branching ratio is

$$BR(\phi \rightarrow \gamma f_0(q^2\bar{q}^2) \rightarrow \gamma\pi\pi) \simeq BR(\phi \rightarrow \gamma a_0(q^2\bar{q}^2) \rightarrow \gamma\pi\eta) \sim 10^{-4}, \quad (1)$$

and in the $K\bar{K}$ molecule model it is

$$BR(\phi \rightarrow \gamma f_0(K\bar{K}) \rightarrow \gamma\pi\pi) \simeq BR(\phi \rightarrow \gamma a_0(K\bar{K}) \rightarrow \gamma\pi\eta) \sim 10^{-5}. \quad (2)$$

*Talk presented by V.V. Gubin

It is easy to note that in the case $f_0 = s\bar{s}$ and $a_0 = (u\bar{u} - d\bar{d})/\sqrt{2}$ (so called $s\bar{s}$ model [10]) the branching ratios $BR(\phi \rightarrow \gamma f_0 \rightarrow \gamma\pi\pi)$ and $BR(\phi \rightarrow \gamma a_0 \rightarrow \gamma\pi\eta)$ are different by factor of ten, which should be visible experimentally.

In the case when $f_0 = s\bar{s}$ the suppression by the OZI rule is absent and the evaluation gives [7, 9]

$$BR(\phi \rightarrow \gamma f_0(s\bar{s}) \rightarrow \gamma\pi\pi) \simeq 5 \cdot 10^{-5}, \quad (3)$$

whereas for $a_0 = (u\bar{u} - d\bar{d})/\sqrt{2}$ the decay $\phi \rightarrow \gamma a_0 \rightarrow \gamma\pi\eta$ is suppressed by the OZI rule and is dominated by the real K^+K^- intermediate state breaking the OZI rule [7, 9]

$$BR(\phi \rightarrow \gamma a_0(q\bar{q}) \rightarrow \gamma\pi\eta) \simeq (5 \div 8) \cdot 10^{-6}. \quad (4)$$

Imposing the appropriate photon energy cuts $\omega < 100$ MeV, one can show [9] that the background reactions $e^+e^- \rightarrow \rho(\omega) \rightarrow \pi^0\omega(\rho) \rightarrow \gamma\pi^0\pi^0$, $e^+e^- \rightarrow \rho(\omega) \rightarrow \pi^0\omega(\rho) \rightarrow \gamma\pi^0\eta$ and $e^+e^- \rightarrow \phi \rightarrow \pi^0\rho \rightarrow \gamma\pi^0\pi^0(\eta)$ are negligible in comparison with the scalar meson contribution $e^+e^- \rightarrow \phi \rightarrow \gamma f_0(a_0) \rightarrow \gamma\pi^0\pi^0(\eta)$ for $BR(\phi \rightarrow \gamma f_0(a_0) \rightarrow \gamma\pi^0\pi^0(\eta))$ greater than $5 \cdot 10^{-6}(10^{-5})$.

Let us consider the reaction $e^+e^- \rightarrow \phi \rightarrow \gamma(f_0 + \sigma) \rightarrow \gamma\pi^0\pi^0$ with regard to the mixing of the f_0 and σ mesons. We consider the one-loop mechanism of the R meson production, where $R = f_0, \sigma$, through the charged kaon loop, $\phi \rightarrow K^+K^- \rightarrow \gamma R$, see [7, 8, 9]. The whole formalism in the frame of which we study this problem is discussed in [9]. The parameters of the f_0 and σ mesons we obtain from fitting the $\pi\pi$ scattering data, see [9].

In the four-quark model and $s\bar{s}$ model we consider the following parameters to be free: the coupling constant of the f_0 meson to the $K\bar{K}$ channel $g_{f_0K^+K^-}$, the coupling constant of the σ meson to the $\pi\pi$ channel $g_{\sigma\pi\pi}$, the constant of the $f_0 - \sigma$ transition $C_{f_0\sigma}$, the ratio $R = g_{f_0K^+K^-}^2/g_{f_0\pi^+\pi^-}^2$, the phase θ of the elastic background and the σ meson mass. The mass of the f_0 meson is restricted to the region $0.97 < m_{f_0} < 0.99$ GeV. Treating the σ meson as an ordinary two-quark state, we get $g_{\sigma K^+K^-} = \sqrt{\lambda}g_{\sigma\pi^+\pi^-}/2 \simeq 0.35g_{\sigma\pi^+\pi^-}$, where $\lambda \simeq 1/2$ takes into account suppression of the strange quark production. So the constant $g_{\sigma K^+K^-}$ (and $g_{\sigma\eta\eta}$) is not essential in our fit.

As for the reaction $e^+e^- \rightarrow \gamma\pi^0\eta$ the similar analysis of the $\pi\eta$ scattering cannot be performed directly. But, our analysis of the final state interaction for the f_0 meson production show that the situation does not changed radically, in any case in the region $\omega < 100$ MeV. Hence, one can hope that the final state interaction in the $e^+e^- \rightarrow \gamma a_0 \rightarrow \gamma\pi\eta$ reaction will not strongly affect the predictions in the region $\omega < 100$ MeV. Based on the analysis of $\pi\pi$ scattering and using the relations between coupling constants we predict the quantities of the $BR(\phi \rightarrow \gamma a_0 \rightarrow \gamma\pi\eta)$ in the $q^2\bar{q}^2$ model, $K\bar{K}$ model and the $q\bar{q}$ model where $f_0 = s\bar{s}$ and $a_0 = (u\bar{u} - d\bar{d})/\sqrt{2}$.

The fitting shows that in the four quark model ($g_{f_0 K^+ K^-}^2/4\pi \sim 1 \text{ GeV}^2$) a number of parameters describe well enough the $\pi\pi$ scattering in the region $0.7 < m < 1.8 \text{ GeV}$, see [9]. We predict $BR(\phi \rightarrow \gamma(f_0 + \sigma) \rightarrow \gamma\pi\pi) \sim 10^{-4}$ and $BR(\phi \rightarrow \gamma a_0 \rightarrow \gamma\pi\eta) \sim 10^{-4}$ in the $q^2\bar{q}^2$ model.

In the model of the $K\bar{K}$ molecule we get $BR(\phi \rightarrow \gamma(f_0 + \sigma) \rightarrow \gamma\pi\pi) \sim 10^{-5}$ and $BR(\phi \rightarrow \gamma a_0 \rightarrow \gamma\pi\eta) \sim 10^{-5}$.

In the $q\bar{q}$ model the $f_0(a_0)$ meson is considered as a point-like object, i.e. in the $K\bar{K}$ loop, $\phi \rightarrow K^+ K^- \rightarrow \gamma f_0(a_0)$ and in the transitions caused by the $f_0 - \sigma$ mixing we consider both the real and the virtual intermediate states. This model is different from $q^2\bar{q}^2$ model by the coupling constant which is $g_{f_0 K^+ K^-}^2/4\pi < 0.5 \text{ GeV}^2$. In this model we obtain $BR(\phi \rightarrow \gamma(f_0 + \sigma) \rightarrow \gamma\pi\pi) \simeq 5 \cdot 10^{-5}$ and taking into account the imaginary part of the decay amplitude only, which violates the OZI rule, we get $BR(\phi \rightarrow \gamma a_0(q\bar{q}) \rightarrow \gamma\pi\eta) \simeq 8 \cdot 10^{-6}$.

The experimental data from SND and CMD-2 detectors support the four quark nature of the f_0 and a_0 mesons, see Fig.1 and Fig.2. and also [11, 12, 13, 14]. The obtained parameters for f_0 meson from SND detector are $m_{f_0} = 971 \pm 6 \pm 5 \text{ MeV}$, $g_{f_0 K^+ K^-}^2/4\pi = 2.1 \pm_{0.56}^{0.88} \text{ GeV}^2$, $R = 4.1$ and $BR(\phi \rightarrow \pi^0\pi^0\gamma) = (1.14 \pm 0.1 \pm 0.12) \cdot 10^{-4}$, see the dashed line on Fig.1.

As for reaction $e^+e^- \rightarrow \gamma\pi^+\pi^-$, the analysis shows that the study of this reaction is an interesting and rather complex problem.

The main problem is the large background process of final pions radiation. The f_0 state in this reaction could be studied only by observing the interference patterns in the total cross-section and in the photon spectrum [15, 16]. As it was shown in [16], since the Fermi-Watson theorem for the final state interaction due to the soft photons in the reaction $e^+e^- \rightarrow \rho(s) \rightarrow \gamma\pi^+\pi^-$ is not valid, the phase of the amplitude $\gamma^*(s) \rightarrow \rho \rightarrow \gamma\pi\pi$ does not determined by the s-wave phase of $\pi\pi$ scattering. The analyses of the interference patterns in the reaction $e^+e^- \rightarrow \phi + \rho \rightarrow \gamma f_0 + \gamma\pi^+\pi^- \rightarrow \gamma\pi^+\pi^-$ should be performed taking into account the phase of the elastic background of the $\pi\pi$ scattering, the phase of the triangle diagram $\phi \rightarrow K^+ K^- \rightarrow \gamma f_0$ and the phase of the $f_0 - \sigma$ complex in the $\phi \rightarrow K^+ K^- \rightarrow \gamma(f_0 + \sigma) \rightarrow \gamma\pi\pi$ amplitude. The whole formalism for the description of these reactions and the resulting pictures were stated in [9, 15, 16].

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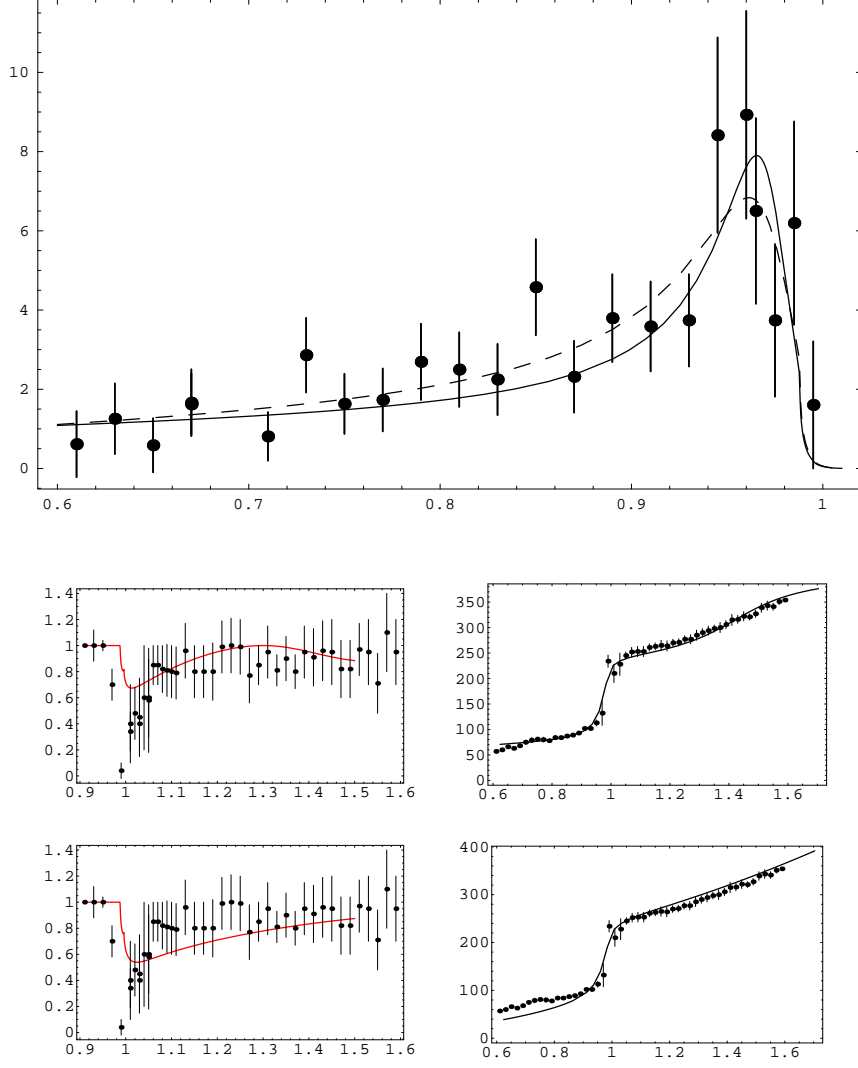


Figure 1: The simultaneous fit of the spectrum of the differential cross section $d\sigma(e^+e^- \rightarrow \gamma(f_0 + \sigma) \rightarrow \gamma\pi^0\pi^0)/d\omega$ with mixing of the f_0 and σ mesons (solid line) and of the $\pi\pi$ scattering data (first row). The branching ratio for this fit is $BR(\phi \rightarrow \gamma\pi^0\pi^0) = 2.8 \cdot 10^{-4}$. The dashed line is the spectrum of the f_0 meson without mixing with the σ meson. The $\pi\pi$ scattering for this fit is in the second row.

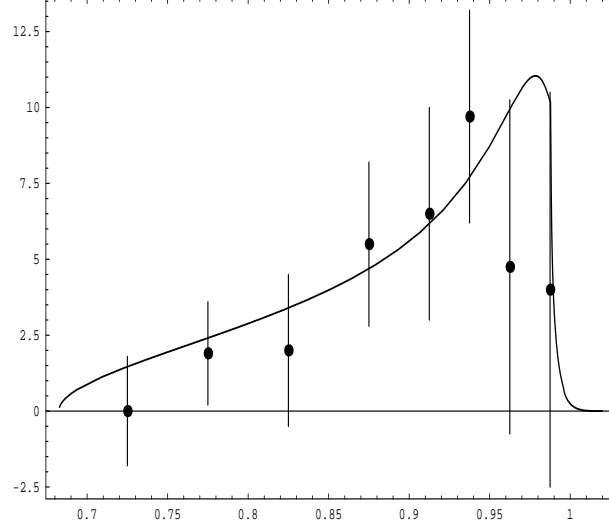


Figure 2: The fit of the spectrum of the differential cross section $d\sigma(e^+e^- \rightarrow \gamma a_0 \rightarrow \gamma\pi^0\eta)/d\omega$. Parameters of the fit are $m_{a_0} = 986 \pm_{10}^{23}$ MeV, $g_{a_0 K^+ K^-}^2/4\pi = 1.5 \pm 0.5$ GeV^2 and $BR(\phi \rightarrow \gamma\pi^0\eta) = (0.83 \pm 0.23) \cdot 10^{-4}$.

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